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Neutrinos and Muons from Atmospheric Charm

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Abstract

We evaluate the fluxes of neutrinos and muons from charmed particles produced by cosmic ray interactions with air nuclei. Using next-to-leading order perturbative QCD, we compare our results with calculations based on a PYTHIA Monte Carlo evaluation of charm production. We investigate the sensitivity of our results to the choice of parton distribution functions and the cosmic ray spectrum. Perturbative QCD yields larger lepton fluxes than the PYTHIA evaluation. The flux of muons from charm dominates the muon flux from pion and kaon decays for energies above $\sim 10^5$ GeV.

1 Introduction:

Neutrinos and muons are produced in the atmosphere from primary cosmic ray interactions with air nuclei. The range of energies of the neutrinos and muons determines their source: at energies below 10-100 TeV, muons come from pion and kaon decays. Muon neutrinos and electron neutrinos come from those same decays as well as from muon decay, depending on the energy. These lepton fluxes are termed ‘conventional’, in contrast to muons and neutrinos that come from the decays of charmed particles, denoted ‘prompt’.

Current interest has been focused on the observations of atmospheric muon neutrinos and electron neutrinos by the Super-Kamiokande experiment (Y. Fukuda et al., 1998). Interpretations of these data rely on the conventional neutrino flux calculations. One interpretation of the measured deficit of muon neutrinos is that muon neutrinos are massive and oscillate into tau neutrinos, which are not detected in the Super-K experiment. A test of this hypothesis would be evidence of tau neutrino appearance through detection of $\nu_\tau \rightarrow \tau$. A background flux of tau neutrinos comes from tau neutrinos produced directly in the atmosphere by charm particle decays, namely, $D_s \rightarrow \tau \nu_\tau$, followed by the decay of the tau itself.

Charmed particle contributions to the high energy muon flux may be the explanation of underground measurements which appear to be larger than conventional flux calculations predict, as summarized by Bugaev et al. (Bugaev et al., 1998). The deviation appears in the TeV energy region for muons.

We present here our results for muon and neutrino fluxes calculated using next-to-leading order (NLO) perturbative QCD. We focus on the muon fluxes above 100 GeV, where we examine the energy at which the crossover from conventional dominated to prompt dominated flux occurs. In addition, we present our evaluation of the tau neutrino flux from D_s decays in the atmosphere for ν_τ energies above 20 GeV and the corresponding event rates.

2 Calculational Method:

The calculation of the prompt lepton fluxes relies on the semi-analytic method using approximate cascade equations. Details of the method can be found in Lipari (1993) and in Pasquali, Reno and Sarcevic (1999). The lepton fluxes depend on the incident cosmic ray flux. Initially, we assume that the incident cosmic ray flux is comprised of protons, and that at the top of the atmosphere, the proton flux $\phi_p(E) = 1.7 (E/\text{GeV})^{-2.7}$ for $E < 5 \cdot 10^6$ GeV and scales as $174 (E/\text{GeV})^{-3}$ for $E \geq 5 \cdot 10^6$ GeV, in units of $(\text{GeV cm}^2 \text{ s sr})^{-1}$. This is the same incident flux used by Thunman,

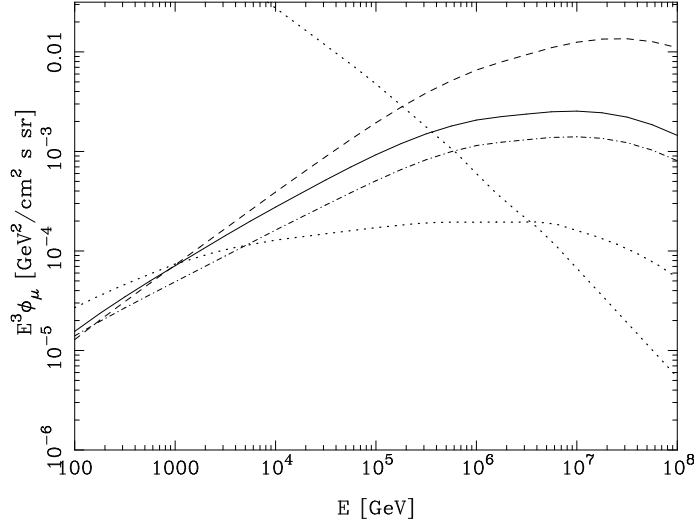


Figure 1: The vertical prompt atmospheric muon flux scaled by E^3 versus muon energy for CTEQ3 (solid) and MRSD₋ (dashed) with $M = 2\mu = 2m_c$, for CTEQ3 with $M = \mu = m_c$ (dot-dashed) and the Thunman, Gondolo & Ingelman (1996) parameterization of the vertical prompt and conventional muon fluxes (dotted).

Gondolo and Ingelman (1996) in their evaluation of the prompt lepton fluxes using the Monte Carlo program PYTHIA.

Of particular importance for charm production is the Z -moment,

$$Z_{pj} = 2f_j \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E/x_E)}{\phi_p(E)} \frac{1}{\sigma_{pA}(E)} \frac{d\sigma_{pA \rightarrow c\bar{c}}(E/x_E)}{dx_E}, \quad (1)$$

where $x_E = E/E_p$, the energy of the outgoing charmed hadron divided by the incident nucleon energy, and f_j is the fraction of charmed particles which emerge as hadron j , as outlined in Pasquali, Reno and Sarcevic (1999).

To evaluate the differential cross section for charm production, we chose a charmed quark mass $m_c = 1.3$ GeV as it yields the best consistency with the experimental data summarized by Frixione, Mangano and Nason (1998). Our default parton distribution functions are CTEQ3 (Lai et al., 1995), however, for comparison, we also used the MRSD₋ set (Martin, Stirling & Roberts, 1993). Our factorization scale (M) and renormalization scale (μ) were chosen as either m_c or $2m_c$, as noted on Fig. 1. To include NLO corrections, we have parameterized in energy and x_E the ratio of the NLO to leading order distribution $d\sigma/dx_E$.

3 Muon Flux:

Our results for the vertical prompt atmospheric flux at sea level, scaled by E^3 , are shown in Fig. 1 by the solid, dashed and dot-dashed lines. All fluxes shown are the sum of particle plus antiparticle. The dotted lines show the Thunman, Gondolo and Ingelman (1996) vertical prompt and conventional muon fluxes. The prompt flux is isotropic below $\sim 10^7$ GeV due to the fact that essentially all charmed particles decay below that energy. At higher energies, the turnover in the flux curve indicates that some charmed particles are not decaying in the region between where they are produced and sea level.

The dashed curve based on the MRSD₋ distributions should be considered as an upper limit, as the parton distribution functions are larger at small parton x than the results reported by HERA

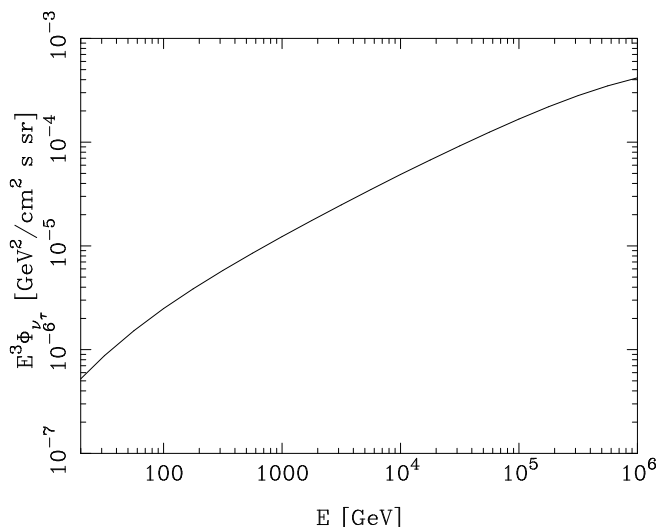


Figure 2: The prompt atmospheric tau neutrino flux scaled by E^3 versus tau neutrino energy.

experiments (Breitweg et al., 1999, Adloff et al., 1997, Derrick et al., 1996). The CTEQ3 distribution functions are a better fit. The solid line in Fig. 1 can be parameterized by

$$\log_{10}[E^3 \phi_\mu / (\text{GeV}^2/\text{cm}^2 \text{s sr})] = -5.79 + 0.345x + 0.105x^2 - 0.0127x^3, \quad (2)$$

where $x = \log_{10}(E/\text{GeV})$. The crossover from conventional to prompt flux occurs at $E \sim 200 - 600$ TeV according to Fig. 1, so perturbative QCD production of charm in the atmosphere cannot explain the deviation of the muon flux from the conventional flux predictions summarized by Bugaev et al. (1998).

The electron neutrino and muon neutrino fluxes from charm are essentially identical to the prompt muon flux shown in Fig. 1. The conventional muon neutrino flux is on the order of 1/5 of the conventional muon flux, while the conventional electron neutrino flux is $\sim 1/150$ of the conventional muon flux.

4 Tau Neutrino Flux:

The atmospheric tau neutrino flux, in the absence of neutrino oscillations, comes primarily from D_s and τ decays. The branching fraction for $D_s \rightarrow \tau \nu_\tau$ is taken to be 4.3% (Gonzalez-Garcia & Gomez-Cadenas, 1997), and tau decay channels $\tau \rightarrow \nu_\tau \mu \nu_\mu$, $\nu_\tau e \nu_e$, $\nu_\tau \pi$, $\nu_\tau \rho$ and $\nu_\tau a_1$ are included. A discussion of the calculation is outlined in Pasquali and Reno (1999). The resulting flux, using the CTEQ3 parton distribution functions and $M = 2\mu = 2m_c$ is shown in Fig. 2. The flux is shown for a tau neutrino energy range from 20 GeV to 10^6 GeV. Over this range, the unidimensional approximation is valid, the charged particles are relativistic and geomagnetic corrections are negligible (Agrawal et al., 1996). The atmospheric tau neutrino flux is isotropic since over the whole energy range, the decay lengths of the D_s and τ are short compared to the height of production.

Event rates for charged current $\nu_\tau + \text{nucleon} \rightarrow \tau X$ conversion are low. In one kilometer-cubed of water equivalent volume, the number of conversions for tau energies above 20 GeV is 110 events per year. In a Super-Kamiokande size detector with water volume of $5 \cdot 10^{-5} \text{ km}^3$, and allowing for a tau range equal to its time dilated decay length, the event rate per year, for the 20 GeV tau energy threshold, is on the order of 0.55 events. Discussions of higher energy thresholds and the effects of $\nu_\mu \rightarrow \nu_\tau$ oscillations are found in Pasquali and Reno (1999).

5 Discussion:

We have evaluated the contributions of charmed particle decays to the atmospheric lepton fluxes. For ν_τ fluxes, the D_s decays are the dominant source. To reduce uncertainties, the charmed mass was chosen to fit accelerator data on charm production, however, we have extrapolated our differential cross sections well beyond the measured regime. In particular, the parton distribution functions below parton $x = 10^{-5}$ are assumed to have the form, e.g., $xg(x) \sim x^{-\lambda}$. For x below some critical value x_c , this extrapolation should be invalid due to shadowing effects.

In an effort to estimate the effect of shadowing, we have considered $x_c = 10^{-6} - 10^{-4}$, below which we have set $\lambda = 0.08$. This shadowing affects the prompt fluxes at $E \sim 10^4 - 10^6$ GeV, with the lower onset due to $x_c = 10^{-4}$. It is unlikely that $x_c = 10^{-4}$ is realistic in view of the data from HERA, including recent measurements at scales above ~ 1 GeV (Breitweg et al., 1999). At $E = 10^8$ GeV, for $x_c = 10^{-4}$ the solid line in Fig. 1 dips to almost $4 \cdot 10^{-4}$, while for $x_c = 10^{-6}$, the flux is 2/3 of the solid curve. The flattening of the small- x parton distribution functions doesn't change our qualitative conclusions about the crossover between conventional and prompt, however, it does indicate that our fluxes above $E \sim 10^6$ GeV have significant theoretical uncertainties.

The atmospheric lepton fluxes are directly proportional to the primary cosmic ray flux at the top of the atmosphere, as well as weakly dependent on the primary flux through the Z -moments, e.g., as in Eq. (1). Since the atmospheric lepton fluxes come from averages of many interactions, the use of the superposition model, in which a nucleus of mass A is equivalent to A nucleons, is a good approximation (Engel et al., 1992). Consequently, what is relevant in the lepton flux calculation is the number of nucleons per energy-per-nucleon. As indicated in Section 2, we have used two power laws for the flux ($E^{-2.7}$ and E^{-3}), with a critical energy of $5 \cdot 10^6$ GeV for the transition between powers. If we use the same powers, but move the critical energy to 10^5 GeV, the new fluxes begin to deviate from the fluxes in Fig. 1 at $E \sim 10^4$ GeV. The solid curve drops by a factor of $\sim 1/3$ at $E = 10^8$ GeV for this choice of critical energy. The transition from conventional to prompt muons occurs at a higher energy, on the order of $E \sim 10^6$ GeV.

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